Experiments in Granular Dynamics.

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For systems comprised of many particles in or near thermal equilibrium, statistical mechanics tells us that fluctuations of observable quantities around their average values tend to be small and to have a gaussian distribution. For athermal systems driven far from thermal equilibrium, there exists no general framework such as statistical mechanics, and fluctuations tend to be distributed broader than a gaussian, such that large and catastrophic, but rare events can dominate behavior. This is the case in avalanches in granular materials, or divergence of fluctuations and length scales at the onset of jamming in disordered materials.

I. DYNAMICS OF THE JAMMING TRANSITION

Mahesh M. Bandi, Charles Reichhardt and Robert E. Ecke A remarkably wide variety of materials display glassy behavior where the length and time scales of the material response can vary tremendously. This has important implications for the physical properties of the material such as the yield stress and dynamic response. In a broader context, systems composed of grains can display similar features when a fluidized granular system effectively freezes as in the plugging of hopper flow. A recent theoretical proposal of Liu and Nagel suggests that there is anoverarching description of such systems termed "jamming". This idea has generated tremendous interest as an organizing principle for understanding the complex behavior of glasses, granular materials, foams, colloids etc. Liu and Nagel argue that jamming may be understood through a phase diagram with shear, temperature, and density axes as seen in fig. 1. The system is jammed when within the dome in fig. 1 and unjammed outside it. There is experimental evidence supporting the jamming phase diagram, but the nature of the lines in the phase diagram remains unknown. In particular, the following questions remain unanswered: (1) Are the separations between unjammed and jammed regions true phase transitions (continuous or first order) or crossovers? (2) Is the behavior at jamming universal in the sense that the size, shape, or interactions of the particles are not important? (3) Do the phase transitions exhibit phenomena such as simple scaling or multifractal scaling? At finite temperatures, relaxation times near glass transition are extremely long, so determining the exact location and nature of the transition is difficult. These problems are eliminated on the T = 0 and zero load axis in fig. 1, where jamming occurs at a point referred to as "Point J" as a function of increasing density.

Recent simulations have provided the first direct evidence that jamming at point J is a continous phase transition with a diverging length scale [2], where a disordered assembly of disks was prepared and a single probe particle was repeatedly moved through the system for increasing packing densities. The length scale ξ is defined in terms of the number of surrounding particles that move with the probe particle. As a function of density ϕ, ξ diverges as a power law: $\xi \propto (\phi_c - \phi)^{-\nu}$ with $\nu = 0.65$, where ϕ_c is the critical jamming density.

We are currently performing experiments to test these ideas on a two-dimensional assembly of bidisperse (to avoid crystallization) photo-elastic disks which are birefringent under stress. Preliminary data is in very good agreement with simulation and the theory for the simplest disk system. An individual particle is pulled through the random close-packed array of disks which will have an adjustable area fraction. The response of moving the particle through this 2D system is probed by measuring the fluctuations in the pulling force and the positions and the photo-elastic

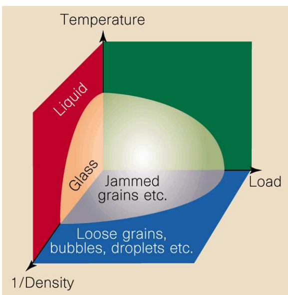

FIG. 1: Proposed Phase diagram of the Jamming transition Source: [1].

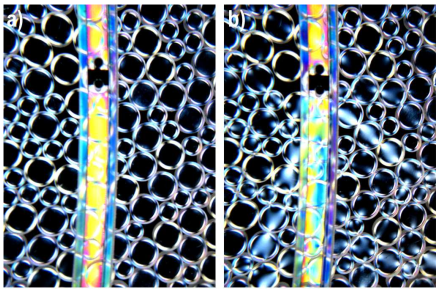

FIG. 2: Photoelastic stress experiment. Yellow line: rod holding driven bead (black rectangle). Left: Unstressed sample. Right: Force chains appear when driven bead moves.

stress response of the particles, as shown in fig. 2. The spectrum of force fluctuations and the length scale of stress chains that cause the fluctuations will be measured as a function of particle density. We plan to also characterize the nature of the diverging length scale based on the number of surrounding particles that are perturbed. Similar experiments will be performed for particles with different sizes and shapes to determine when and how the critical behavior arises.

II. SUB-SURFACE FORCE, DENSITY AND VELOCITY MEASUREMENTS IN GRANULAR INCLINED HOPPER FLOWS.

Mahesh M. Bandi and Robert E. Ecke Granular flows down a rough inclined plane presents a simple yet important system for the study of basic rules that govern granular dynamics. Despite intensive experimental and numerical study such flows are still not well understood. The majority of experiments report on flow properties in narrow channels where the velocity is measured as a function of depth by directly viewing grain motion through side walls. Such a configuration is however imperfect owing to friction with confining vertical walls. Recent work has studied flows in wide channels concentrating primarily on surface flow measurements.

The scaling of velocity with layer thickness in such flows can be understood by a consideration of bulk Bagnold rheology [3]. In this theory, the shear stress varies with the shear rate $\dot{\gamma}$ like $\sigma_{zz} \simeq \dot{\gamma}^2$. With a linear dependence of shear stress on the vertical coordinate z, this leads to a vertical variation of the down-plane velocity of $u(z) \simeq h^{3/2}[1-((h-z)/h)^{3/2}]$ (u being the velocity at depth z and h the flow thickness). Thus, the surface velocity $u = u(h) \simeq h^{3/2}$ so that the scaling $u/\sqrt{g}h$ vs. h is expected to yield straight lines with zero intercept. Although such scaling was reported in experiments involving glass spheres and numerics with idealized spherical particles, recent experiments [4] have shown deviations from this result with strong dependence on material properties.

The recent results therefore bring the Bagnold theory into question, begging measurements of velocities and densities in the bulk. We plan to design probes (optical or mechanical) that allow such measurements in the bulk, a regime thus far unexplored, and hope to elucidate how these measurements bear upon the scaling properties in connection with Bagnold arguments.

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